



A Survey of Power Electronics Applications in Aerospace Technologies

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A SURVEY OF POWER ELECTRONICS APPLICATIONS IN AEROSPACE TECHNOLOGIES

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ABSTRACT

The insertion of power electronics in aerospace technologies is becoming widespread. The application of semiconductor devices and electronic converters, as summarized in this paper, includes the International Space Station, satellite power system, and motor drives in 'more electric' technology applied to aircraft, starter/generators and reusable launch vehicles. Flywheels, servo systems embodying electromechanical actuation, and spacecraft on-board electric propulsion are discussed. Continued inroad by power electronics depends on resolving incompatibility of using variable frequency for 400Hz-operated aircraft equipment. Dual-use electronic modules should reduce system development cost.

I. THE POWER ELECTRONIC SYSTEM [1-2]

A power electronic system can comprise a modular power electronic subsystem (PESS) connected to a source and load at its input and output power ports, respectively. The third port of PESS is connected to the system control, as shown in Fig. 1. PESS has been described as a power device module, intelligent power module, smart power device, power control module and, more recently, power electronic building block (PEBB) of the Office of Naval Research-initiated program [1-2].

The next three sections discuss the commonly used power semiconductor devices and their resident electronic converters, and electric motor drive technologies which are enablers in the 'more electric' technology (MET) for aero-space vehicle upgrades.

I-1. Power Semiconductor Devices

The semiconductor devices metal-oxide-semiconductor field effect transistor (MOSFET), insulated gate bipolar transistor (IGBT), mos-controlled thyristor (MCT) and gate-turn-off thyristor (GTO) represent the cornerstone of modern power electronic converters. They are fully controllable.

Their applications depend on their power and frequency characteristics.

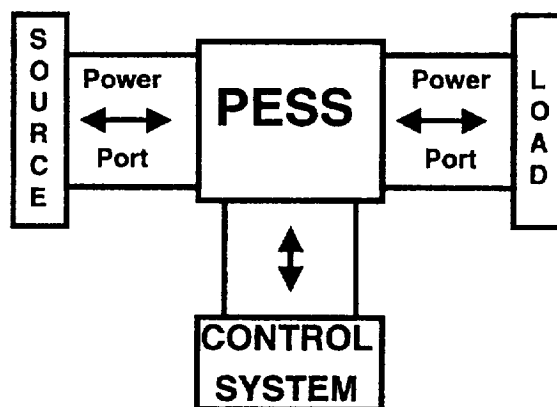


Figure 1.— Three-Port Power Electronic System Structure.

The unipolar, voltage-controlled MOSFET is relatively very fast, requires only minimal snubbing due to its low switching losses, and is protected from breakdown by its inherent positive temperature coefficient of resistance. Its drain resistance increases with temperature. The device is used in applications of few MHz and few watts to few kilowatts, such as in voltage-source pulse-width-modulated inverter (PWMI) and a zero-voltage switching (ZVS) converter rated at 0.1 to 2kVA and 0.5 to 2MHz.

The IGBT, a hybrid of a MOSFET and a turn/off bipolar junction transistor (BJT), is a MOS-gated device. When used in 0 to 300kVA, 1.5 to 5kHz voltage-source PWMI and 20 to 150kVA, 40kHz voltage-source converter drives, the IGBT requires minimum cooling, is more reliable, experiences reduced voltage spikes at turn-off, and exhibits improved thermal life.

The GTO is turned-on/off by gate current pulses. Turn-off-induced spike in the anode voltage can cause hot spots in, and breakdown of the device. A snubber can protect the GTO the high switching losses of

which limit its use to 1.0 to 2.0kHz PWM. Example application areas are 0.75 to 1.5kVA, 500 to 600Hz voltage-source PWMI and 2 to 12MVA, 700 to 1200Hz ZVS inverter.

The MCT is a MOS-gated device with a high turn-off current gain. With switching speed comparable to that of IGBT, the MCT shows promise for application in snubbed voltage-source inverters at 0 to 100kVA and 2kHz, zero-current switching (ZCS) at 150kVA and 40kHz, and ZVS converter at 20 to 150kVA and 25kHz. The above devices are constituent parts of electronic converters which permeate aerospace power systems.

I-2. Power Electronic Converters [3-4]

Aerospace power systems have a considerable real estate of DC power usage. Over the past decade, AC power has emerged as a 'driver' for developing MET's. This has increased the use of power electronic converters to condition and control power in the related systems. The high frequency converters of interest and their devices are noted in Fig. 2 [3].

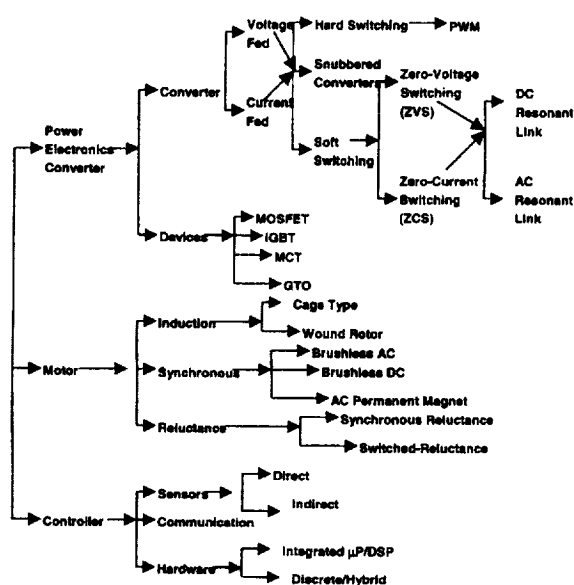


Figure 2.—Options for 'More Electric' Technology (MET).

The semiconductor devices in a hard-switching PWMI are stressed during turn-on/off modes. Capacitive and inductive stray effects compound the resulting switching losses. The PWMI AC voltage output is harmonic-rich, variable-frequency (VF), and commercially used in motor drives. The PWMI is characterized by limited power range and low switching frequencies, with attendant acoustic noise and reduced efficiency. However, it has low Volt-Ampere rating, and is relatively easy to control.

The **snubbed converter** employs switching similar to that of the PWMI. It incorporates a series inductive snubber to limit the inrush-current through its devices. A parallel capacitive snubber limits the device voltage, and reduces device stress. High switching losses are dissipated in the snubber.

The **zero-current switching (ZCS) converter** uses an inductive snubber for device turn-off without current flow. Similarly, the **zero-voltage switching (ZVS) converter** employs a capacitive snubber for device turn-on, with an anti-parallel diode conducting. The converters have high switching frequency, lossless devices, high efficiency and reliability.

The **Resonant DC-Link (RDCL)** in Fig. 3 and **Resonant AC Link converters** overcome the limitations of PWMI. The RDCL converter has low switching losses, heat dissipation and acoustic noise, higher operating frequency and reliability, and reduced dv/dt and di/dt, resulting in low electromagnetic interference. Eliminating the Resonant Tank from Fig. 3 yields the conventional hard-switched, voltage-source PWMI [3].

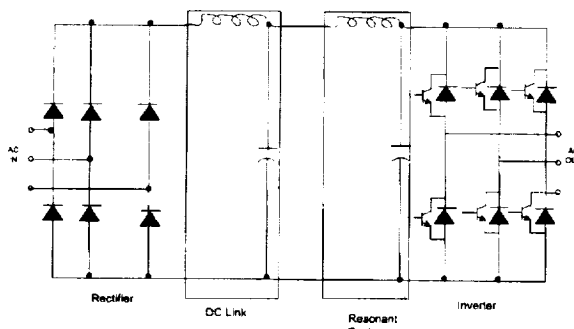


Figure 3.—The Conventional Resonant DC Link Inverter.

DC-DC converters have been used in aerospace power systems to provide the required voltage for the secondary distribution network. The basic topologies are the **step-down (buck)** and **step-up (boost)** converters for various load requirements [4]. For a given input voltage, the average output voltage is obtained by switching the electronic devices at constant frequency, while adjusting the device 'ON' duration.

Electronic converters constitute the heart of motor drives which are essential for electromechanical actuation (EMA) in MET.

I-3. Motor Drive Technologies [5-12]

The electric motor is the workhorse in a drive system. Drive characteristics depend on the motor, the power circuit, electronic devices and the controller. Power rating, operating speed range, environment,

fault tolerance, reliability, performance, thermal capability and cost affect motor selection for an application [5].

In the past, the excellent drive performance and low initial cost of DC machines made them the primary choice for servo applications. Their built-in commutators, high maintenance and spark-inducing brushes hinder DC machine use in drives. "Brushless" motors have emerged from coupling DC, AC synchronous and induction motors with electronic controllers. The resulting maintenance- and spark-free brushless DC machine (BLDCM) or permanent magnet synchronous motor (PMSM), switched reluctance motor (SRM) and induction motor (IM) have higher torque/inertia ratio, peak torque capability, power density and reliability than the DC brush motor.

The permanent magnet in the rotor of a BLDCM produces an armature current-independent field. The commutatorless BLDCM has laterally stiff rotor which permits higher speed, especially in servo applications. The intra-stator placement of the rotor improves heat conduction which increases electric loading, and yields a higher torque/amp, better effective power factor and higher efficiency. BLDCM-based drives are popular, due to their performance and price improvements. Disadvantages include the need for shaft position sensing and more complex electronic controller.

The IM has been the traditional workhorse for fixed and variable speed drive applications. It is rugged, relatively inexpensive and almost maintenance-free. The rotor slip-dependent torque production worsens the performance and decreases the efficiency of the motor. In the fractional and low integral hp range requiring dynamic performance, high efficiency and a wide speed range, the complexity of induction motor drive makes the BLDCM favorable.

The gear-less, direct-application SRM drives are widely accepted. Their applicability to aircraft engine starter/generator has been demonstrated [6-7]. The motor design and converter topologies of the drive have undergone significant research and development in over two decades [8-12]. The series connection of the converter phase-leg switches to the motor phase winding prevents shoot-through fault by the converter switches. The motor is economical, compact in construction, and has high torque-to-inertia ratio, high torque output at low-to-moderate speeds, and faster response in servo systems. Its drawbacks are higher torque ripple and acoustic noise, complex control, and the need for an absolute rotor position sensor for the controller to establish the phase current pulses.

II. AEROSPACE POWER SYSTEMS [2]

The advent of MET for aerospace systems has focused attention on AC-, and hybrid DC- and AC-based

power management and distribution (PMAD) systems. The schematics in Figs. 4 and 5 show a commonality in the use of electronic converters, photovoltaic (PV) solar arrays and batteries [2]. In aerospace systems, PEBB-related integration issues are the level of power and frequency range, application- and mission-dependent extreme temperature range, weight and size, electromagnetic interference and performance. Resolution of these issues is expected to promote expeditious insertion of electronic modules in aerospace technologies.

III. POWER ELECTRONICS APPLICATION IN AEROSPACE TECHNOLOGIES

The International Space Station (ISS), satellite power systems, MET, starter/generator system, reusable launch vehicles, flywheel technology and on-board electric propulsion are discussed to highlight the important role of power electronics in these systems.

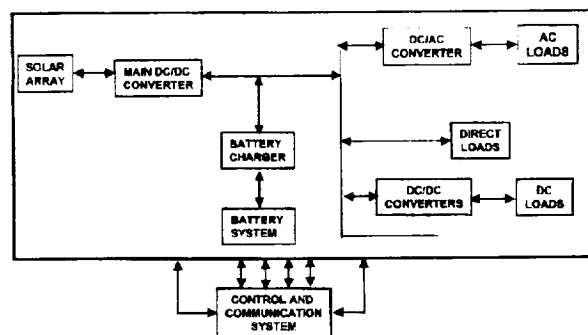


Figure 4.—DC-PMAD-Based Electric Power System.

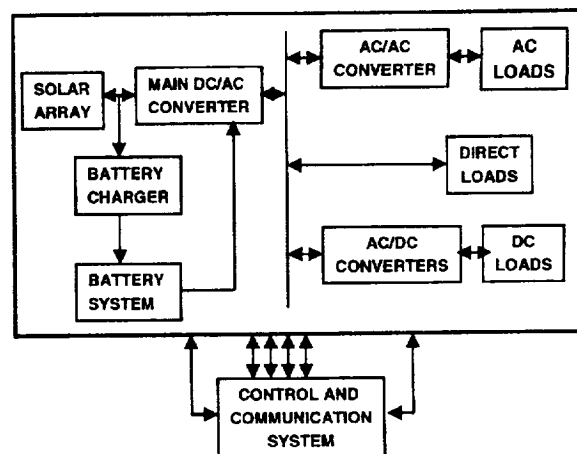


Figure 5.—AC-PMAD-Based Electric Power System.

III-1. Space Station Power System [13-14]

A single channel diagram, Fig. 6, of the ISS electric power system (EPS) shows a DC network of PV solar

arrays, batteries, power converters, switches and user loads [13]. The networks of 120V American and 28V Russian can exchange bi-directional power flow via American-to-Russian Converter (ARCU) and Russian-to-American Converter (RACU) units. The primary distribution system (PDS) comprises the PV arrays, batteries and the network up to the DC-DC converter units (DDCU's), for 160V to 120V step-down to the secondary distribution system (SDS). The sequential shunt unit (SSU) regulates the voltage output of the PV array. The DDCU's isolate the PDS and SDS from each other, and condition the source power for the SDS. The batteries store energy during insolation periods, and supply load power during orbital eclipse. The battery charge/discharge units (BCDU's) isolate the battery from the primary bus. Remote power controller modules (RPCM's), or switchgears, distribute power to the load converters. The BCDU's, DDCU's and the load converter contain semiconductor switches in their circuitry, thus underscoring the importance of power electronics in the ISS EPS.

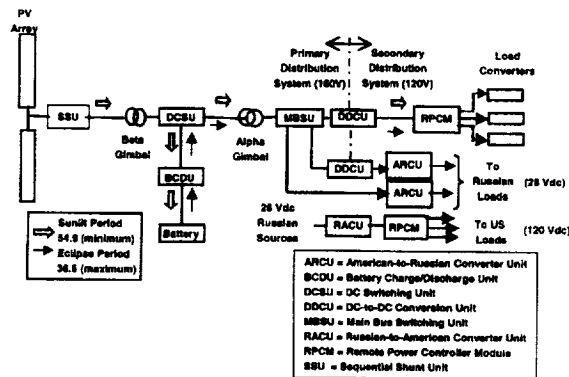


Figure 6.—Single Channel Diagram of ISS Power System.

In their modular form, power electronics are expected to facilitate the control of PMAD and diagnosis of system malfunctions, to yield reliability improvement [14]. Some level of electronic modularity has already been built into some satellite EPS, to permit adaptability of the EPS to various and future programs, with minimal re-design.

III-2. Satellite Power Systems [15]

A partial block diagram of a satellite modular EPS is shown in Fig. 7. It depicts only the north portion of a 'Dual Bus' power system for a geosynchronous satellite [15]. The primary-side elements of the EPS

are the PV arrays, battery and power control unit (PCU). On the secondary side, the PCU embodies the SSU, battery charge and discharge converter modules (BCCM, BDCM), and low voltage converter module (LVCM) of redundant, main bus-connected DDCUs which feed the spacecraft loads via the power distribution unit (PDU). The operation of the satellite

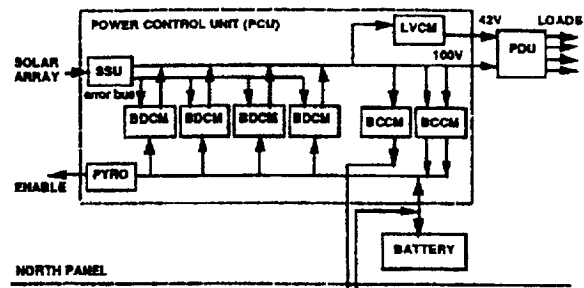


Figure 7.—Block Diagram of Satellite Power System.

EPS is similar to that of the ISS, regarding sunlight and eclipse portions of a mission. The built-in modularity makes it possible to vary battery voltage and output power levels, by adding and removing converter module(s). This feature renders the EPS configurable for future missions. Also, the modularity facilitates power electronics packaging, equipment deployment into space, and needed on-orbit EPS modifications.

The use of power electronics-based motion control systems in selected aerospace systems is discussed next.

III-3. Motor Drive Applications [5, 14, 16-33]

The key elements in electric actuation (EA) for MET are the electric motor, its power electronics, the control system and the actuator load(s) [5]. Lower costs and advances in power electronics and high-speed electric machines have fuelled the interest of technologists, developers and researchers in industry [16-19], Government Agencies [20-23], and academia [24-27], in aerospace motion control systems. A key premise of the MET is to replace the traditionally mounted auxiliary drives and bleed air extraction with integral engine starter/generators (S/G's), electrical-driven actuators and engine-gearbox-driven fuel pumps. The replacement eliminates hydraulic, pneumatic and mechanical power, and minimizes and/or eliminates their associated costs, as well as high pre-flight operation, maintenance and refurbishment of hydrazine-driven auxiliary power units (APU's).

III-3.1. More Electric Technology for Aircraft

Figure 8 shows a conceptual diagram of the Air Force's 'more electric aircraft' (MEA) subsystems [20]. The hydraulic-driven flight control actuators, the engine-gearbox driven fuel pump and air-driven environmental control system (ECS) are electrically powered by electric motor drives. A S/G supplies electric power to a fault-tolerant PMAD subsystem which feeds power to the EA, engine starting, braking, ECS, fuel pump and anti-icing. Uninterrupted power from an integrated APU and battery system provides redundancy and engine start-up.

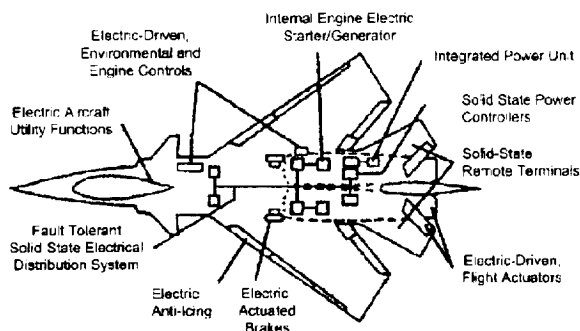


Figure 8.—Concept of More Electric Aircraft.

The candidate electric motor drives for the MET are the IM, BLDCM and SRM drives. For each selected drive in the MET, depending on the application, the EA and its electronic controller must suitably match the safety and reliability of hydraulic actuation. This may require motor drive redundancy, for assured flight and landing. Thus, the built-in redundancy in its independent motor windings due to magnetic isolation, and in power switching circuits by electrical isolation, makes the SRM an attractive choice for fault-tolerant EA. This 'limp home' ability of the SRM has been one of the key factors in its selection by the Air Force in their MEA development [21–22].

III-3.2. Starter/Generators

A general variable speed constant frequency (VSCF) S/G system is shown in Fig. 9 [23]. The machine may be any of the three candidates in Section III-3. During motoring, constant frequency (CF) electrical power from the main AC bus is converted to VF by the bi-directional power converter, and fed to the machine to start the load such as an aircraft engine. In the generating mode, the variable speed load provides mechanical power to run the machine the variable frequency of which is converted to a constant frequency for the main bus. The control system

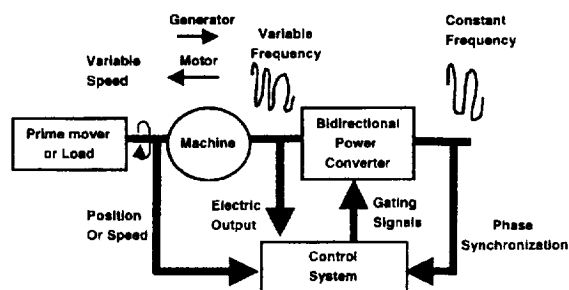


Figure 9.—Typical VSCF Starter/Generator System.

receives inputs from the VSCF sources, and provides gating signals for the converter to maintain proper interface between VF and CF requirements.

III-3.3. Reusable Launch Vehicles

EMA has been under consideration for replacing hydraulic systems used on reusable launch vehicles for thrust vector control (TVC) gimbaling of engines and aerosurface control [28–29]. The projected benefits are as stated in Section III-3. In the early 90's, the then NASA Lewis Research Center (currently GRC) and General Dynamics Space Systems Division cooperated on demonstrating EMA technology readiness to meet the hydraulic TVC requirements for the Atlas Expendable Launch Vehicle [28]. Concurrently, a study by the NASA Kennedy Space Center indicated that the MET would save nearly 66 percent of man-hours needed for hydraulic TVC processing of the Shuttle Solid Rocket Booster [30]. The EMA in Ref. [28] embodied IM drive with a field-oriented control [5, 31–32] for independent control of torque and flux, and a Pulse Population Modulation technique [28] for independent control of voltage and frequency.

A more advanced motor drive is in use for ongoing Government-Industry development of flywheel technology.

III-3.4. Flywheel Technology

United States Government Agencies, Industry and academia are jointly developing advanced flywheel technologies to provide high performance and reliability, and reduced losses in a high-speed, light weight flywheel energy storage system (FESS), peak power and load leveling in spacecraft and aircraft applications [14]. The FESS embodies advanced composite materials-based rotor, low-loss magnetic bearings, high-speed motor-generator set and electronic converter drive. The above efforts and concurrent component technology developments represent an advancement of prior work by the collaborators [33]. NASA GRC has been leading an effort for a combined flywheel energy storage and

attitude control system, namely, integrated power and control system, to enable the development of a low cost, lightweight and higher specific energy spacecraft.

Additionally to conditioning power and enabling bi-directional power and stored energy flow in flywheel systems, motor drives feature in electric upgrade of aircraft pumps, for the same MET benefits.

III-3.5. Servo System Applications

The MET proposes the use of VF motor drives to operate hydraulic and fuel pumps on aircraft. Using high-density motor drives can eliminate the usual size and weight limitations of drives. However, issues of VF incompatibility with 400Hz-operated aircraft equipment such as fuel and hydraulic pumps [19], attendant increase in motor weight to achieve the required torque at high frequencies, and potentially high upgrade cost must be resolved.

By comparison with CF power, VF motor controllers can reduce transient inrush current at motor start. Furthermore, a variable speed motor-driven fuel pump can provide only the required amount of fuel. Also, such a fuel pump can improve aircraft performance by reducing engine gearbox weight and enabling direct integration with the aircraft electronic propulsion and flight control [16].

Additionally to their use in aerospace power systems, electronic converters play an important function in the on-board electric propulsion of spacecraft.

III-4. On-Board Electric Propulsion [34-37]

Power electronics are constituent parts of the power processing unit (PPU) of spacecraft electric propulsion which is credited with reducing launch vehicle requirements, notably for north-south station keeping of commercial geosynchronous satellites [34]. A PPU comprises one or more electronic converters. It provides electric power for the spacecraft thruster, and commands and telemetry interface to the electric propulsion system, as shown in Fig. 10 [35]. The converters may be current-controlled and voltage-fed, to rapidly supply constant current to offset thruster voltage variations, typically during a start-up period.

Small-sized PPUs with a minimal number of lightweight, highly efficient, soft-switching converters yield increased payload and power [36]. Such PPUs can generate high voltage start pulse to ignite as many as four arcjet thrusters for north/south station keeping orbit maneuvers [37], thus reducing propulsion system mass.

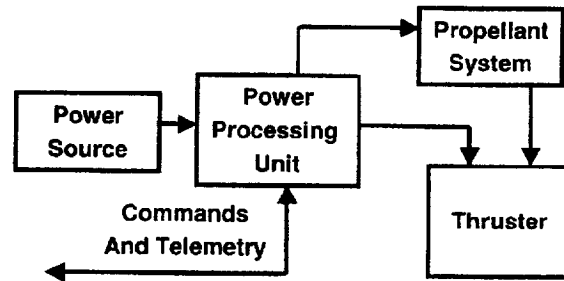


Figure 10.—Electric Propulsion System.

Several challenges must be overcome for continued penetration of power electronics into aerospace systems.

IV. FUTURE TRENDS [14,19,24,38]

VF is currently used in turbo-prop and business jets. The cost and savings attractions of VF are tempered by the potential high cost of VF-upgrade for conventional, 400Hz-operating equipment on aircraft. Reference [19] points out judicious use of power electronics, via a hybrid hydraulic/pneumatic/motor drive design, to circumvent the VF-400Hz aircraft equipment incompatibility.

Continued improvements in power electronic devices and their switching schemes, advances in magnetic materials and capacitors, and better design of motors and electronic controls are expected to ameliorate weight, size and reliability issues of MET application to aerospace systems.

The need for bi-directional converters for battery charge/discharge functions and fixed frequency power and voltage, and expected varying requirements of multiple loads in aerospace systems suggest future use of hybrid AC and DC multi-converters with multi-voltage levels [24].

Increasing use of power electronic modules will require consideration of device ratings, bi-directionality or otherwise of power flow, power density requirements and degree of integration, when developing aerospace systems. Hardware commonality will promote dual-use application of the modules, and decrease system development cost [14]. For instance, NASA-planned development of 2 to 3kW power processor/thruster is expected to provide modular elements for various mission requirements [38].

V. CONCLUSIONS

This paper presents a survey of power electronics applications in aerospace technologies. It encompasses

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